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Managing pile foundation and land cost for high-rise buildings in the early design stages

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ABSTRACT
High-rise buildings in areas with thick layers of sedimentation require deep pile foundations which lead to higher costs. The height, layout and location of high-rise buildings are crucial to reducing costs. The aim of this paper is to propose a cost estimation model for buildings, which includes pile foundation and land cost. The element method for cost control and structural theories are integrated in order to predict costs per m^2 of floor. Specific soil characteristics have been combined with wind and seismic loads. The result of this study is a cost estimation model that allows for the comparison of these different layouts (building height and depth). The effect of land cost and soil conditions (requiring appropriate pile foundation) on the price per m^2 of floor can be calculated. The model can support designers, developers and policy-makers in making decisions in the early design stages.

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Cost estimation; high-rise building; land cost; lateral load; pile foundation; seismic load; soft soil; wind load

Introduction

A reduction in the building foot print can be reached by erecting higher buildings in areas that have the same population density. In this way, more public or green areas can be preserved. In recent years, and as a response to rapid population growth, residential high-rise buildings have become common place for many new housing projects. However, the foundation cost per square metre of floor area of high-rise buildings represents a high percentage of the construction's overall cost. They can vary, to a significant degree, depending on the soft soil conditions as well as different loads, such as dead loads, live loads, earthquakes and wind loads. The need for a model that can control the unit cost of the element 'foundation' for high-rise buildings is therefore crucial.

Two existing types of cost estimation studies can be distinguished: detailed study and studies based on statistical data (1) Cost estimation exists for the detailed design stage, where crucial decisions have already been made and it is already too late to change the project in any significant way. (2) Statistical methods are based on the historical data of constructed buildings (Chan & Park, 2005; Picken & Ilozor, 2003; Tan, 1999). Models suppose a linear correlation between final cost and Karshenas' design parameters (Bowen & Edwards, 1985; Karshenas, 1984; Khosrowshahi & Kaka, 1996; Lowe, Emsley, & Harding, 2006; Singh, 1990; Trost & Oberlender, 2003). The Artificial Neural Networks' (ANNs) multi-linear and nonlinear relationships can be identified between construction costs and parameters (Adeli & Wu, 1998; Arafa & Alqedra, 2011; Bode, 2000; Murat Günaydın & Zeynep Doğan, 2004; Yu & Skibniewski, 2010). A study by Tan (1999) describes that the relationship between construction cost and building height has been impacted upon by technology, building design, demand and institutional factors. The nonlinear regression method, based on construction

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cost and height data for buildings in Hong Kong, was used to visualize the relationship between a building's height and construction cost for the buildings and resulted in a U curve of the function $y = 0.2963 * x^2 - 59.05 * x + 7552$, where x is the building height (m) and y is the construction cost (USD/m^2) (Picken & Ilozor, 2003). These cost models need to be validated and contextualized with historical data, both of which are expensive to collect and difficult to update.

Methodology

Another approach has been followed in this study: the element method for cost control, which was developed as a glass box method (De Troyer, 2008), is further elaborated so that major building parameters (such as width, depth and height) can be changed and so that the effect upon ratios (quantity of element per m^2 of floor) and unit rates of elements are embedded in the model and the total construction costs are calculated (De Troyer, 2003). The effects that building height and footprint area have upon construction costs have also been studied by Chau and his colleagues (2007) but the element method does this in a transparent and adaptable way.

The element method has the ability to consider the effect that changing basic design parameters has in the early design stages; however, the integration of the pile foundation costs, for soft soil conditions, into the cost model is non-existent. Hence, the aim of this paper is to propose a new method for approximate cost estimation for the pile foundation in a soft soil condition at the early design stage. The cost estimation model has the ability to integrate various input parameters: height, depth, subsoil properties, wind and seismic loads.

Structure

The remainder of this paper is organized in the following way. In the section entitled Definition of the design space, assumptions regarding the cases considered and the applicable standards are explained in order to construct the model. The different steps of the process of analysis are: the optimal cost per kN capacity of pile foundation, the correction factor to the shear lag effect of the reinforced concrete rigid frame and the loads place upon foundation by wind and earthquake(s). In the section entitled Results and analysis, results have been reported and discussed in detail. In the section entitled Sensitivity analysis, a parameter study is discussed in order to understand the significant parameters. The last section contains the Conclusions.

Definition of the design space

Building height and structural material

This study focuses on high-rise buildings that have rigid reinforced concrete frames. The number of floors varies from 2 to 25 floors and a floor height of 3.6 m was initially chosen. Moreover, the maximum height of reinforced concrete rigid frames should be around 20–25 floors (Ali & Moon, 2007), because rigid frames are considered to be economical for buildings of up to approximately 25 stories, above which their drift resistance is costly to control (Taranath, 2010).

Soil properties

Traditional methods through which to obtain soil properties are applied, which include soil samples, standards penetration test, cone penetration test (CPT), static and dynamic pile load tests on sites. The CPT for the estimation of static axial pile bearing capacity is the most common situ test for soil properties. CPT is the most applicable soil test for the analysis of pile foundations because of its simplicity, rapid applicability and cost effectiveness (Baziar, Kashkooli, & Saeedi-Azizkandi, 2012; Haldar & Babu, 2008).

The methods accepted by Eurocode 7 for the design of piles must be based, directly or indirectly, upon the results of static pile load tests. However, this pile load test must only be used for the final adjustment of detail design and before the pile foundations are constructed on site. The CPT method has been selected to determine the optimal sizes (depth and section) of piles at the early design stage, as this method is cheap, and often the only one available in the early design phase. This method can predict the results of the pile load test that has to be used in a final stage, relatively well.

Building layout

Rectangular floor plans have been chosen because plan forms, such as L, I, H, U, Z, and Œ shapes, can be combined by the simple rectangular building layouts with settlement joints. Firstly, damages due to vertical settlement differences between different blocks can be avoided by settlement joints to separate building blocks with differing loads. Secondly, the presence of different soil properties in different locations in built-up areas can occur, and can result in different vertical settlements. Thirdly, the natural frequencies of these complex structures depend upon detailed floor plans, specific loads, the building's exact height and are very specific to each case.

Pile foundation approach

In soft soil conditions, such as in the Mekong delta area, pile foundations for high-rise buildings have been commonly constructed by reinforced prefabricated concrete-driven piles or by bored piles. The bored piles can maximize soil-bearing capacity but require more complex technologies and heavy construction equipment, which leads to high construction cost. Bored piles, therefore, should only be used for heavy load foundations, such as bridge foundations. Although Continuous Flight Auger piles, or screw piles, can be alternatives to driven piles for low loads, the reinforced concrete piles are more common in soft soil conditions because they are easy to control regarding quality and for constructing very deep piles. Reinforced concrete piles, with a square section of between 25 and 40 cm, have been chosen for analysis in this study because they are the most frequently used design alternative in a soft soil condition.

Input parameters

Input parameters are subdivided into four groups; firstly, geometrical parameters, such as the number of bays, width of the bays, columns and beam sizes, floor thickness, number of floors and technical parameters like soil properties. The next group contains finishing elements, including finishing layers of external and internal walls. The third group defines load type: wind loads, seismic loads, live and dead loads. The final group includes land costs at different locations. Land costs for new urban areas in Cantho city, including infrastructures, such as sewerage, electricity and road systems, can be found in official documents and in free market transactions. The construction cost of pile foundations are also based on market rates as of 2011. The average USD exchange rate used is 20,000 VND to the USD.

Analysis process for foundation costs

The cost model can be elaborated in six steps. (1) The cost of the optimal size (section and length) was obtained. This depends on the soil's characteristics and cost of reinforced concrete piles that have different sections. (2) The vertical loads (including live and dead loads) are then calculated. (3) The dynamic horizontal loads from wind and seismic activity loads are transferred to the pile foundations. (4) All load cases are combined to find the worst case scenario. (5) The total cost of both pile foundation cost and land cost, per m^2 of floor area, is estimated in order to look for the building's optimal layout. (6) The sensitivity of the model to the parameters estimated is analysed by using the Latin Hypercube Sampling method (Helton & Davis, 2003; McKay, Beckman, & Conover, 1979).

Optimal cost per kN capacity of pile foundations

The general outline of the method can be described as follows: The first point concerns the friction resistance of the soil, as measured through CPT (Figure 1, left). Based on this, the total resistance for a specific section over the whole length can be calculated (Figure 1, right, left line: soil capacity curve P_s). This resistance will be different for different sections, given that their surface areas are different and will increase depending on the depth. The compressive strength of the cross-section of a pile is calculated for a selected concrete type and reinforcement fraction. An empirical reduction fraction is then applied, from certain slenderness points on (pile length over size of square pile), in order to take the slenderness of the pile into account (see Table 1). The soft soil offers no significant lateral support. This will lead to a maximal pile capacity, as represented in Figure 1 right: right line, P_p. At the intersection point of both curves (P_s and P_p) the maximum capacity of the pile is equal to the maximum soil capacity, leading to the optimal use of the pile. The procedure is repeated for each section, since for each section the basic compressive strength is different and the slenderness factor also differs.

The cost per the running metre pile depends on the following parameters: (1) the quantity of steel and concrete per running metre, (2) the cost of driving the pile into the soft soil with a hydraulic press. The cost per running metre is proportional to the section of the pile. The total cost is obtained by multiplying the length at maximum capacity and the unit rate per metre. The cost per kN at the maximum load for each of the sections considered can be obtained by dividing the cost by the bearing capacity. If, from a given depth on, no additional soil resistance is measured by CPT (due to the fact that the layer below that point offers no additional support) then the maximum load is limited to the soil resistance at that depth (below the maximum pile resistance). Since soil characteristics are different at different locations, the cost per kN for different piles, all used at maximum capacity, should be plotted for every single location (Figure 2). Once the total load for a given building has been obtained, the foundation should be designed with a combination of the most cost-effective piles. If both curves, P_s and P_p, do not intersect, then the smallest bearing capacity for both of them should be chosen for the optimal cost.

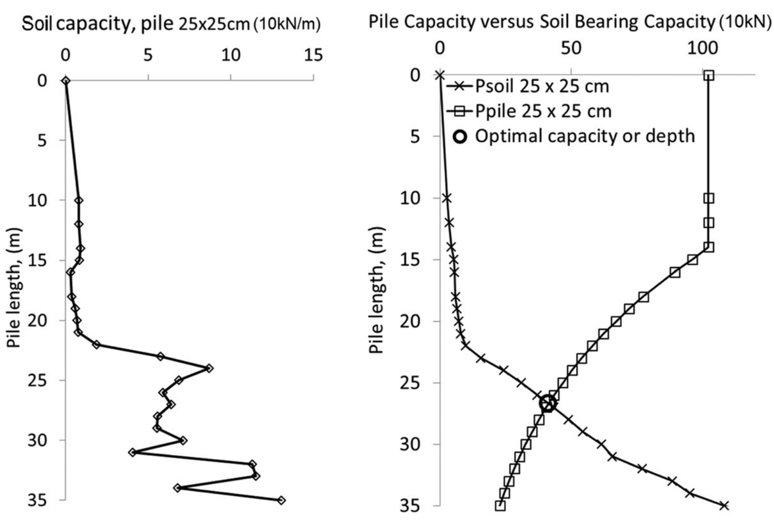

Figure 1. The optimal length pile based on soil capacity; P_{soil} 25 × 25 cm: the pile capacity based on soil properties for pile with section 25 × 25 cm; P_{pile} 25 × 25 cm: the pile capacity based on reinforced concrete piles with section 25 × 25 cm.

Table 1. Slenderness ratio of piles, M. Jacobson.

$\lambda = L/r$	50	70	85	105	120	140
φ	1	0.8	0.59	0.41	0.31	0.23

Fundamental frequency (building period)

The 'Natural frequency' or the 'period' of building is a critical parameter in the seismic design of buildings because of the strong effect on the seismic load's magnitudes. The natural frequency depends on the stiffness and mass of the high-rise building and affects the values of the lateral loads from both the wind (dynamic load of wind) and from earthquakes. The seismic load increases dramatically during the first stage of the spectrum.

The natural frequencies can be calculated accurately using the finite element method. This approach requires detailed structural data from buildings and a huge calculation time to simulate large numbers of frame cases given that the input data needs to be modified for each design alternative. However, a simple method by which to estimate the critical frequency of a wall-frame building was developed with an average absolute error from between 1.6% and 7% for individual frameworks (Zalka, 2001). Statistical methods or empirical formulas have been implemented in most building codes. Goel and Chopra proposed an empirical relation for the fundamental period: $T_{G-C} = 0.053{*}H^{\wedge 0.9}$ (Goel & Chopra, 1997). The European earthquake design code (CEN, 2004a) proposed that the formula of a building period is $T = \mathrm{Ct}{*}H^{\wedge 0.75}$. The Ct is 0.085 for moment-resisting space steel frames, 0.075 for moment-resistant space concrete frames and 0.50 for eccentrically braced steel frames. H corresponds to the total height of buildings in metres. These approaches are suitable

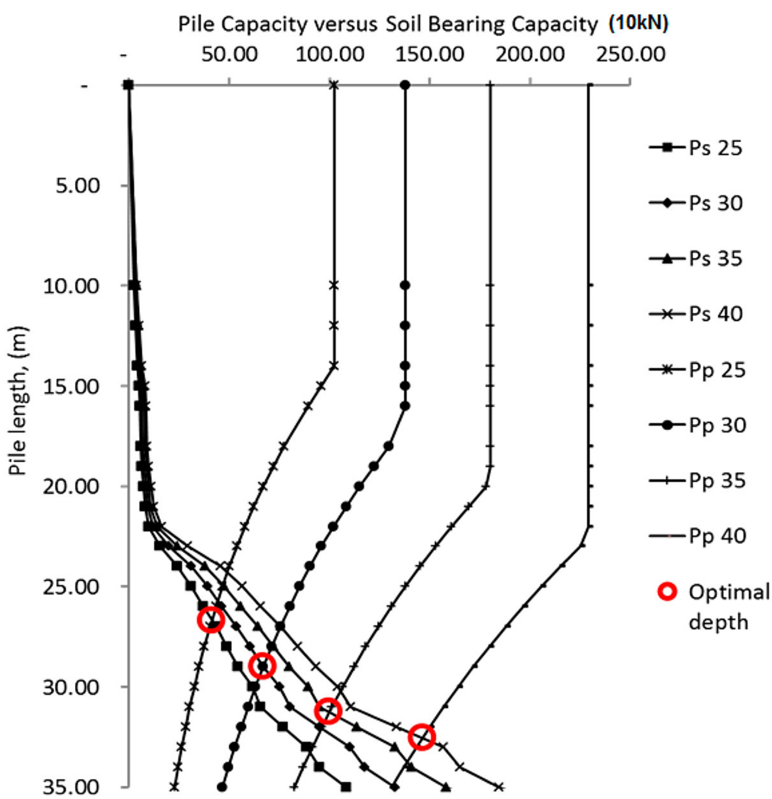

Figure 2. Optimal depth or capacity of different pile sections. P_s 25: the pile capacity based on soil properties for pile with section 25 × 25 cm; P_p 25: the pile capacity based on reinforced concrete piles with a section of 25 × 25 cm.

for moment-resisting framed structures. In this study, the simple empirical formula is used to obtain the building periods.

Loads upon foundation

The aim of the method, described in this section, is to determine the horizontal and vertical loads on the foundation of high-rise buildings, in line with both Vietnamese and Eurocodes standards. The parameters describing a building with a rectangular floor plan will be the height, width and depth and the span between columns in both directions.

Vertical loads: dead loads and live loads

Vertical dead loads will be derived for common materials (concrete, masonry, tiles) and sections (for walls, floors, beams and columns). The density of reinforced concrete is 2500 kg/m^3. The clay brick wall has a density of 1500 kg/m^3. The live load for people and furniture is 3 kN/m^2 floor area for all kinds of functional rooms.

Wind load

The procedure by which to calculate the wind was based on the EN 1991-1-4. The static and dynamic components were obtained using the code's second procedure, which provided more reliable results than the first procedure (Steenbergen, Vrouwenvelder, & Geurts, 2012). The formula for wind force was also used as provided (CEN, 2004b).

The European wind design code and Vietnamese design standards apply wind speeds at an average of 10 min registered over a 50-year period. Design wind velocity is 38.8 m/s. The wind pressure in Cantho city is 0.95 kN/m^2 in urban areas.

The wind speed increases, in a parabolic way, with the height and is influenced by the roughness of the terrain. For every floor, one must consider total wind force as proportional to the façade area (story height) operating at a specific height. The moment, at the foundation level, is the sum of moments for each floor (Figure 3).

Seismic load

In the Mekong Delta area seismic activities, ground acceleration or ground motions are relatively uncommon. Therefore, buildings have not been considered by most designers to require anti-seismic infrastructures for low seismic activity cities, such as in Vietnam (Ngo, Nguyen, & Nguyen,

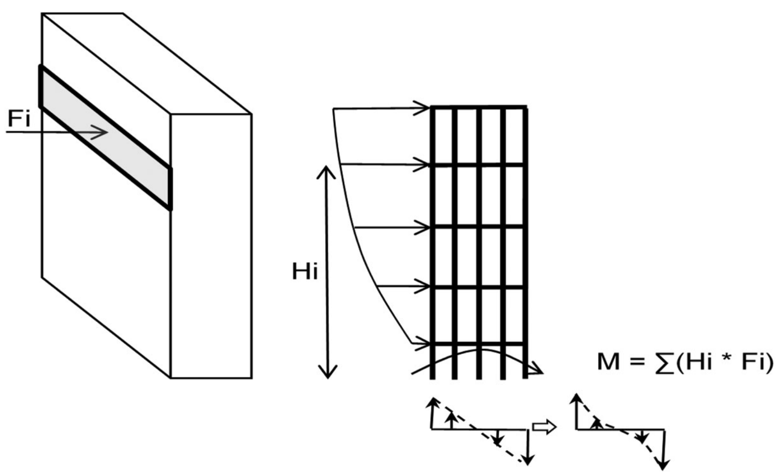

Figure 3. The wind load and vertical axial forces of columns, at ground floor, with or without the shear lag phenomenon.

2008). However, they were not aware of seismic hazards occurring from distant earthquakes. Unforeseen damages to the high-rise buildings may occur where the seismic loads have not been carefully considered. Damage from the seismic effect can reduce the life cycle periods of buildings and can generate life loss.

An earthquake can generate complex dynamic transformation. Detailed simulations have shown that, for the size considered, mass and the structural characteristics, the first transformation using the building structure is the most critical. The building period can be estimated by the traditional method: T (second) = 0.075 * H^ (3/4), (CEN, 2004a). The procedure for the whole building is as follows: the mass of each floor and the walls going half a floor up and for half a floor below are concentrated at one point. The impact force, F_i, depends upon the height based on the following formula:

$$F_i = F_\mathrm{b} \frac{z_i \cdot m_i}{\sum z_i \cdot m_i},$$

where F_i is the horizontal force acting on storey i; F_b is the seismic base shear; $\mathrm{m_i}$ is the storey masses; Z_i is the heights of the masses m_i above the level of application of the seismic action (foundation or top of a rigid basement).

The moment at the foundation is the sum of all of the moments generated by the forces of each of the concentrated masses. Thus, the sum of the moments generated by the shear forces of each floor determines the moment at the foundation (Figure 4).

The procedure to calculate the horizontal force for each floor height, above, is based on ground type E of the CEN standard (CEN, 2004a), represented by soft soil condition at Cantho and calculating the seismic load for the elastic response spectrum. In this case, the average ground acceleration at Cantho is 0.0669 m/s^2.

Correction factor to shear lag effect of the reinforced concrete rigid frame

Frame deformations are generated by bending, shearing in beams and by columns and joint rotation. These effects reduce the cantilever stiffness and are called the 'shear lag effect'. The difference

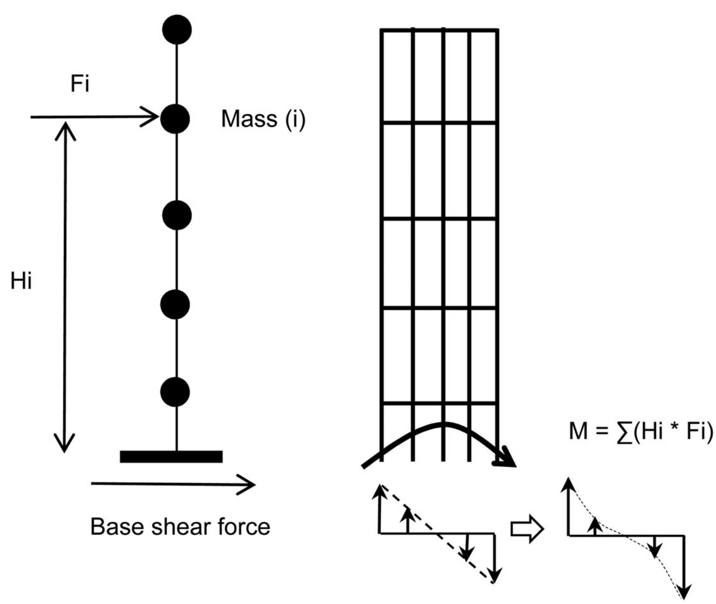

Figure 4. The seismic load and vertical axial forces of columns, at ground floor, with or without the shear lag phenomenon.

between vertical axial forces, as predicted by ordinary beam theory, is the assumption that plane sections remain plane. The actual distribution, due to shear lag, is illustrated in Figure 5. The axial forces at the front and at the rear façades have the largest values. In the first analysis, in the perfect elastic model, the load upon each row of heads of the pile group will increase, with respect to the distance from the neutral line (Figure 6).

In this first approach (Figure 6(a)) vertical loads and horizontal loads are transferred to the foundations through a simplified method in which reaction forces are proportional in a linear way to the external load (linear elastic approach). A finite element method is used for the second step. The structure is simplified to a column and beam structure with stiff internal connections. No transfer of moments, just above the foundation, is supposed (Figure 6(b)). The output of the finite element method is visualized via 'deformed shape' image (Figure 6(c)).

In the second phase, finite element calculations are used to predict vertical forces in all columns in the rigid frames by varying the frame components. The frame components are the sizes of the columns, beams, number of bays and number of floors. Then, the ratio of the total compression axial forces of both (with and without the shear lag effect) is obtained and an approximate formula, to correct for the shear lag effect, can be sought out. We define a correction factor $Y = F_{fe}/F_{sim}$. F_{fe} is the total compression forces obtained through the finite element method. F_{sim} is the total compression forces obtained through the simplified elastic mode.

The vertical load, including dead and live loads, will be transmitted to the pile's foundations which are composed of 'cost – optimal – piles'. The exact grouping of piles around different columns is elaborated in the normal design process at a later phase. In this preliminary cost estimation we can only check how the total number of piles can be derived from the simplified calculation. We have compared the average compression forces of the two approaches (Figure 6(a) and 6(c)). The point loads for the two approaches are compared with respect to the different number of bays and for the bay's different sizes combined with different building heights. The building's height, the number of bays and the approximate correction factors vary, but can still be determined

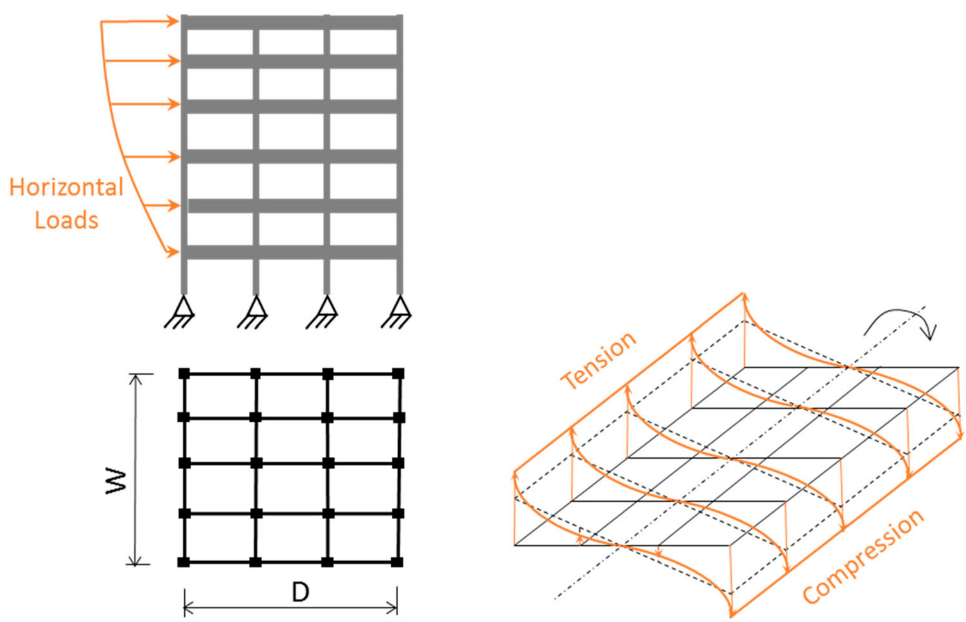

Figure 5. In the rigid frame, the axial force distribution under horizontal loads (right) is affected by the shear lag phenomenon where the horizontal loads are transferred to vertical axial forces at the foundation level. D is the depth and W is the width of the building.

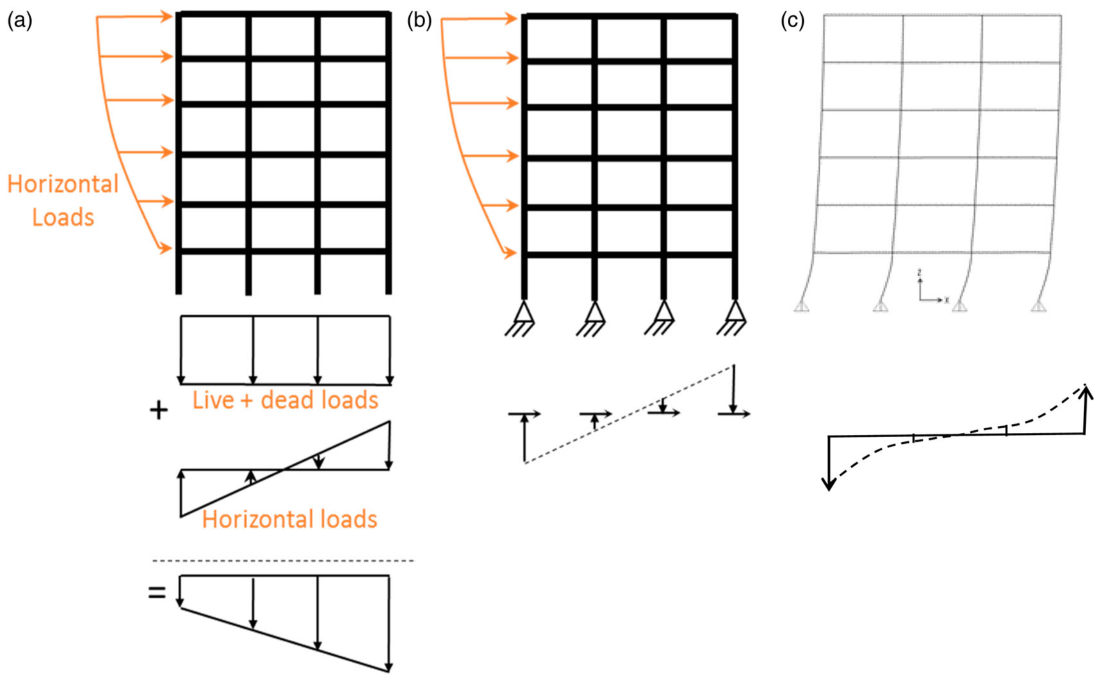

Figure 6. Distribution of axial forces from the lateral loads with and without the shear lag effect. (a) distribution axial forces from dead, live and lateral loads and total axial load; (b) axial force of lateral loads without the shear lag effect; (c) axial force of lateral loads with the shear lag effect, result from the finite element method.

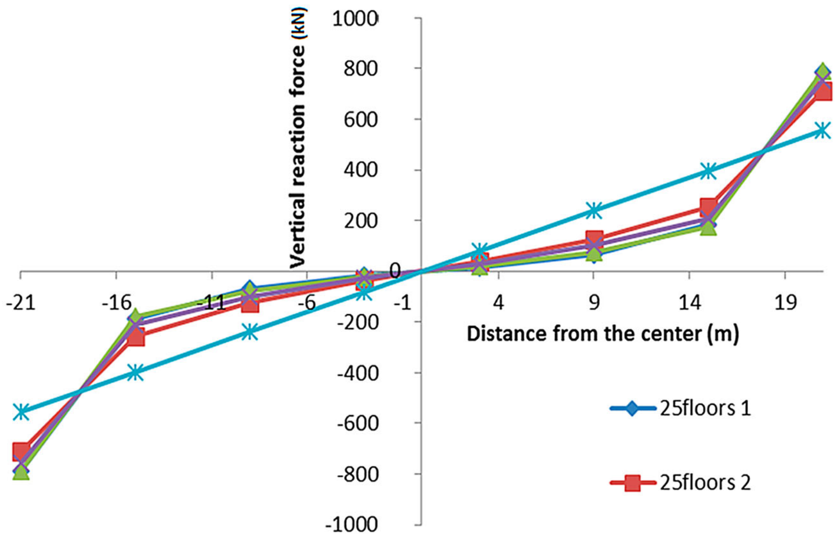

Figure 7. The shear lag effect of a rigid 7 bays, 25 floors, 6 m bay and 3.6 m floor height. Axial forces of frame. Total loads with the shear lag effect are smaller than total loads with true cantilever.

(Figure 7). The correction factor of total axial forces is strongly related to the number of floors, by formula $Y = 1.39 - 0.0075{*}X$; where X is the number of floors, which ranges from between 2 and 25 floors (Figure 8).

Results and analysis

Cost optimal piles for five locations at Cantho

The optimal capacity of different pile sections, from between 25 and 40 cm with steps of 5 cm each, at five locations in the city is illustrated in Figure 9. The cost per kN capacity of optimal piles at different pile sections at five locations in the city are illustrated in Figures 10 and 11, based on the construction cost of the pile foundation, and upon the optimal depths of the piles. At Binh Thuy, which has a

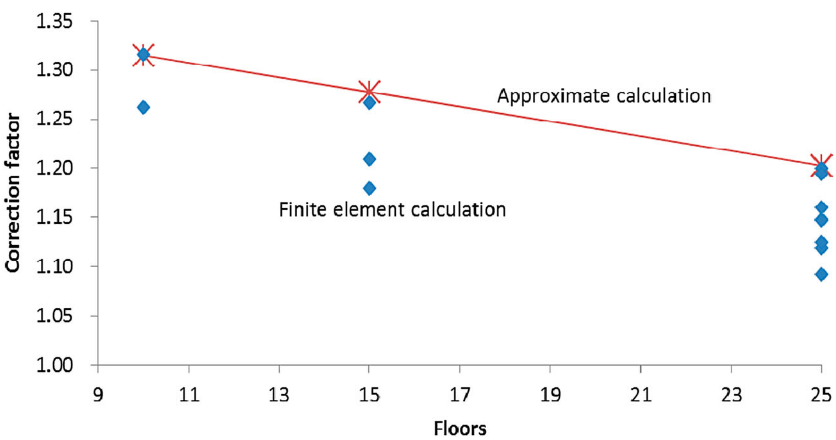

Figure 8. Correction factor for shear lag in the rigid frames: $Y = 1.39 - 0.0075{*}X$; X is the number of floors. The approximate calculation has been selected on the safe side of the correction factors.

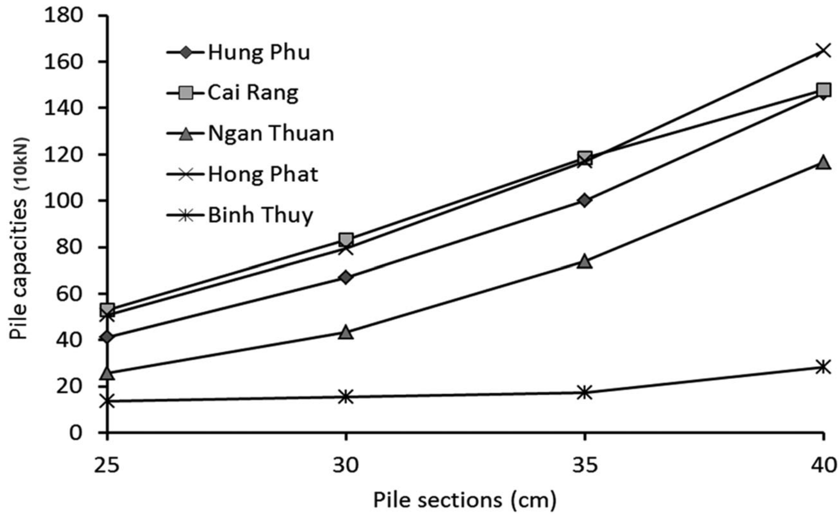

Figure 9. The optimal pile capacity based on both soil and structural properties (P_s: soil-bearing capacity of the pile, P_p: capacity of the pile based on reinforced concrete structure).

thick, soft soil layer (Figure 1) the cost per kN capacity goes up when increasing the section of the pile from (25×25 cm) to (40×40 cm).

Lateral loads transfer to pile foundations

The lateral loads, including wind and seismic loads, are transferred to piles according to vertical axial forces based on the true cantilever (Euler theory). The second step is to adjust them with correction factors to take the 'shear lag effect' into account. A whole range of building depths, from between 12 and 36 m, were analysed to address the relationship between load components and their impact upon piles. With small building depths, the lateral loads generate large vertical loads on the pile foundations, as shown in Figure 12. The vertical loads, generated by lateral loads, vary from between 30% and 130% of the total vertical load from both live and dead loads, depending on the building's depth

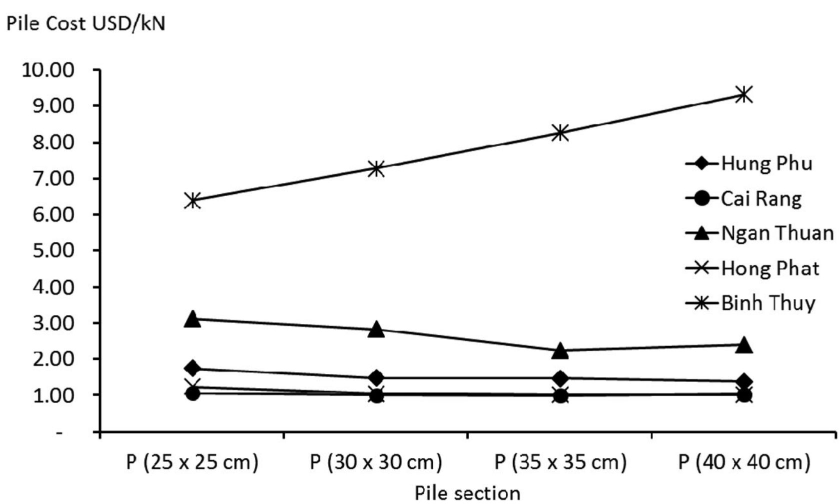

Figure 10. Cost of one ton capacity for the optimal pile foundation in Cantho.

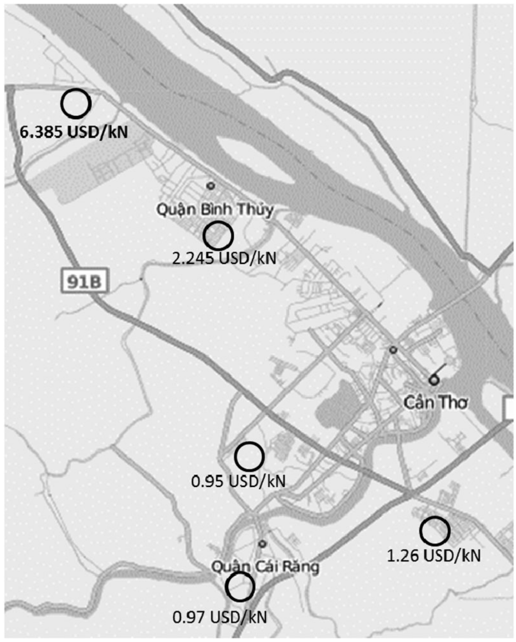

Figure 11. Cost of one ton capacity of pile foundation in five places in Cantho.

and height. The lateral loads are significant in designing foundations for high-rise buildings in soft soil conditions. For smaller building depths, the vertical loads per square metre floor area generated by the wind load are larger than the seismic load if the building height that is greater than eight floors. There is a significant increase in the vertical load of the seismic load at floor 9 due to the elastic response spectrum.

In order to compare different buildings, the total load is divided by the total floor area. The vertical dead and live loads remain constant per m^2 of floor area. Lateral loads per square metre of floor area have been calculated for five building depths as well as different building heights between 1 and 25 floors (115 design options) and then a regression formula has been elaborated in order to estimate the load on the foundation based on two parameters: building depth and height (see the formula in Figure 13). This formula will be used for optimization models in the following section.

Foundation cost integrated with building height and land costs

Based on the three main parameters (height, depth and land costs), the cost of pile foundations, for different building depths, increases almost linearly with the building's height (Figure 14). The interplay of four main parameters (height, depth, costs of foundation and land) will be clarified in this section. In the graphs below, the land cost chosen is 100 USD/m^2, based on the market price from web sites for land price in 2011 in Cantho; the foundation cost is 7.0 USD per kN based on the minimum construction cost in the weakest soil properties; the depths have been changed from 12 to 36 m with a 6 m bay. If building depth increases, the minimum costs are almost constant on a low level (Figure 15). These results change slightly according to several different building depths because seismic loads are related to the masses of the structure and the wind pressure has a minor increase when the width decreases. Figure 14 shows a jump in foundation cost with a similar effect being observable in vertical loads on piles in Figure 12 because of the changing of fundamental frequency related to building height. Since the length of the building has almost no influence on the horizontal loads, the graphs are constructed for an average length of 50 m.

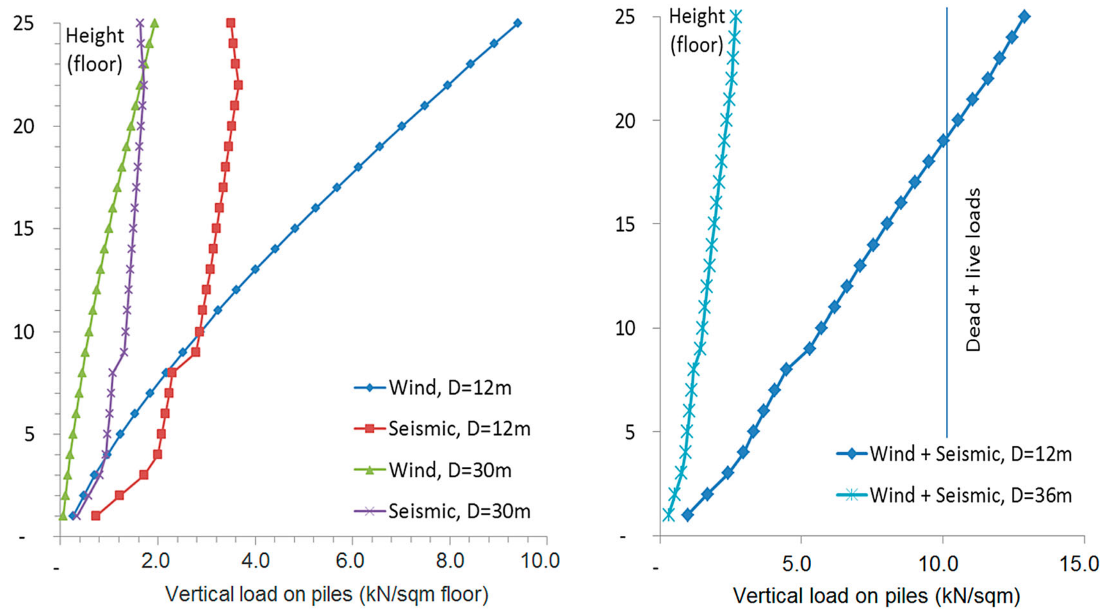

Figure 12. Vertical loads on foundation (kN/m² floor area).

$$VL = a + \frac{b}{D} + c * H + \frac{d * H}{D}$$

a=956.117; b=-680.684;

c=-2.555; d=182.497;

VL: vertical load on foundation
(0.01kN/sqm floor area

D: building depth (m)

H: building height (m)

(R^2=0.99)

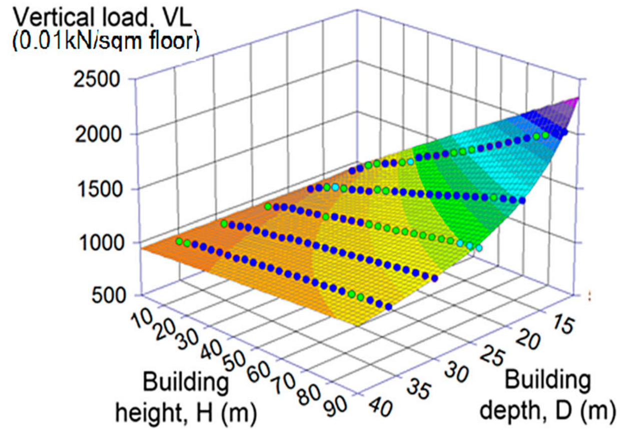

Figure 13. Total vertical load per square metre floor area (dead, live, wind and seismic loads) for different building depths and heights are appropriately calculated by the formula.

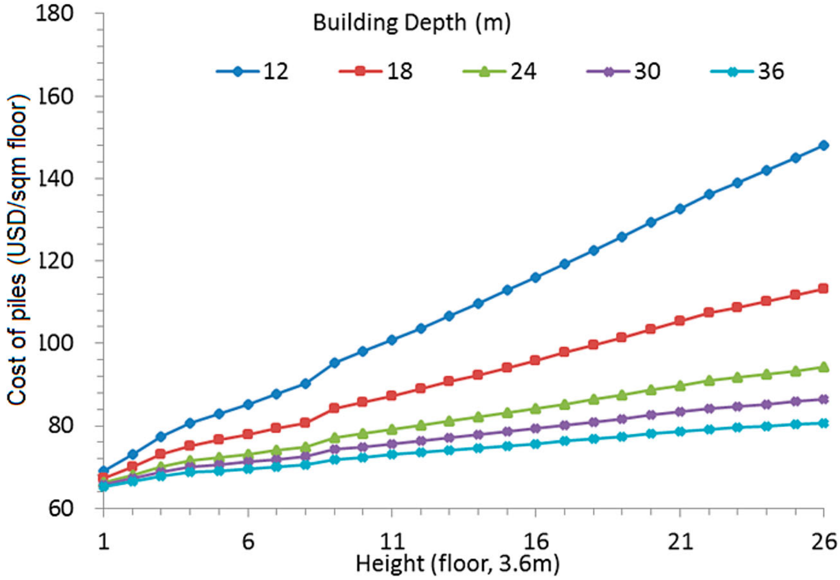

Figure 14. The cost of pile foundation, per one square metre floor area, is evaluated with the pile foundation cost 70USD/ton capacity.

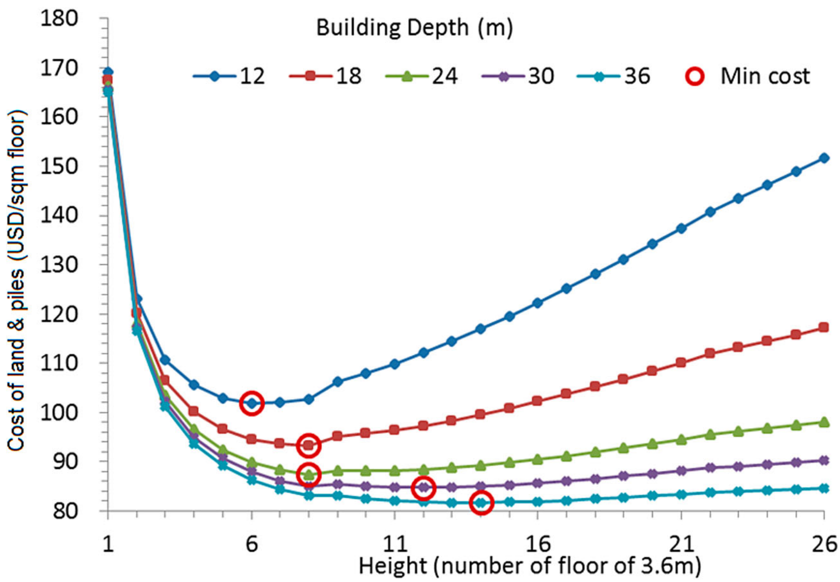

Figure 15. The cost of land and pile foundation per one square metre floor area. Land cost = 100USD/sqm; Pile cost = 70USD/ton.

Sensitivity analysis

Four parameters (land cost, the pile foundation cost, depth and height) have been analysed to determine their effects on the total cost. Clearly, the land cost decreases hyperbolically as the building's height increases. The sensitivity of the model varies, depending on different building's heights, as shown in Figure 16.

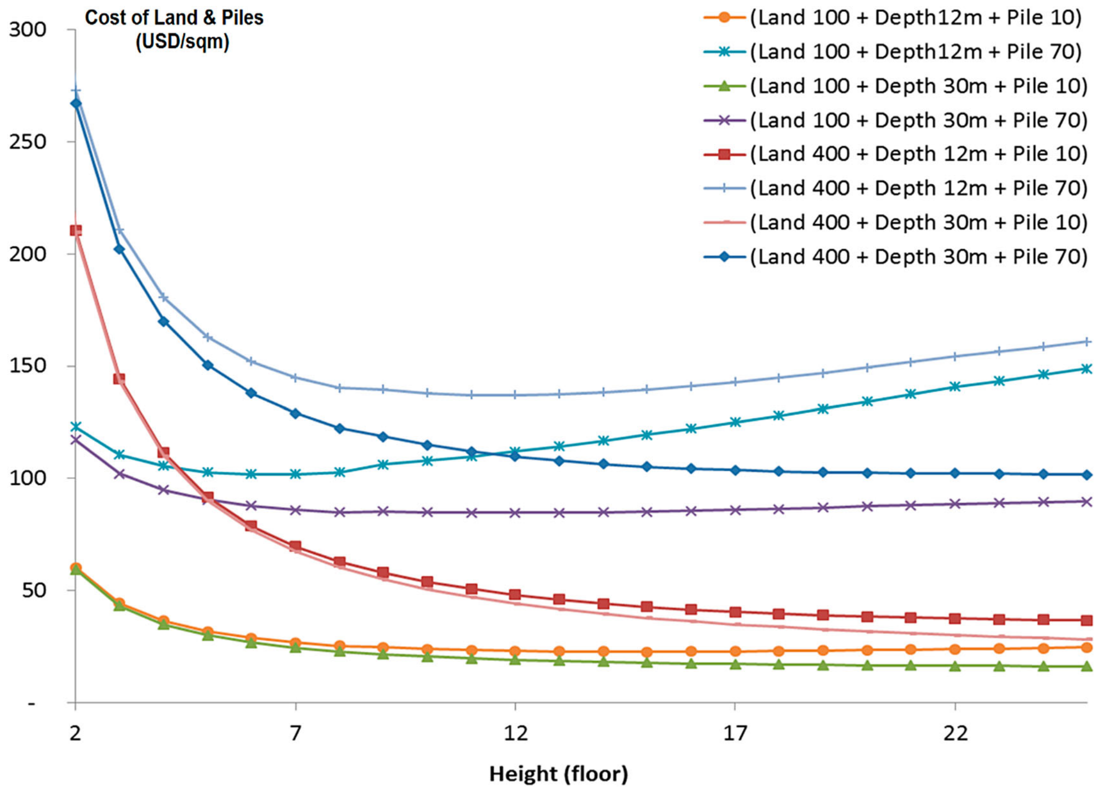

Figure 16. Sensitivity analysis of four parameters.

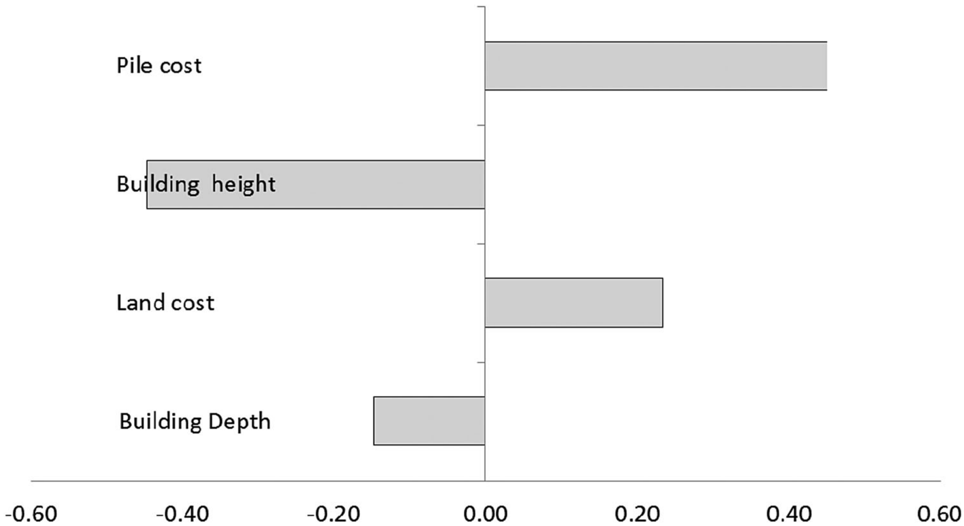

Figure 17. Sensitivity of four parameters are ranked using SimLab or R, the higher absolute value on the horizontal axis indicates the higher impact level of the parameter. A negative sign for the other parameters means that when we increase the parameter, the outputs decreases. Sensitivity values are dimensionless and vary between −1 and 1.

The standardized regression coefficient, the global sensitivity analysis approach, which is based on a linear regression of the output on the input vector, is used to analyse this sensitivity. The most sensitive parameters are the pile foundation cost and the building height, as shown in Figure 17.

Conclusions

There are four significant conclusions as follows: (1) Based on the case study analysis of Cantho city, the Mekong Delta, buildings between 6 and 15 floors lead to the lowest foundation cost per m^2 of floor, depending on particular soil properties in specific locations. (2) Although it is the critical load for high-rises buildings, the seismic force has not been considered by designers in this city. (3) At the early design phases, when crucial design decisions need to be made, useful information for designers and developers can be found in the cost estimation model and in the graphical representations of the end results. In soft soil conditions, where the cost of a pile foundation is higher, the impact of building layout, height and depth can be derived. (4) The model could also have been developed for rigid steel frame buildings. Further research is required to couple this model with finite element programmes in order to calculate fundamental frequency. However, there are some limitations that this current model has not yet covered. Firstly, the model is not appropriate for walled structures because of the distribution of axial forces in the columns for instance. Secondly, the fundamental frequency (building period) of complicated floor plans is not integrated. This can be obtained by using the finite element programmes.

The original contribution of this work consists of the integration of a fast estimation of foundation costs in the element method for cost control. This allows in an early design phase, when different compositions are compared (number of floors, building depth in the two directions), to analyse the cost per m^2 of floor. The element method for cost control allows for a transparent view on the contribution to the cost of different elements (foundation, external walls, roof, internal walls, …) including land and infrastructure.

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Disclosure statement

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